The Detection of Single Positive Ions, Electrons and Photons by a Secondary Electron Multiplier

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A secondary electron multiplier tube has been developed and used successfully for counting single positive ions, electrons and photons. This tube has twelve electrodes covered with a thin layer of beryllium. Tests have shown that with 330 volts per stage this tube will multiply the primary current by a factor of 10^5. The use of guard ring insulation and electrostatic shielding for the final collecting electrode has reduced the background current to an extremely low value. The last electrode was connected to the grid of the first tube in a linear amplifier. In order to count single positive ions or electrons the tube was waxed to the end of a simple magnetic spectrograph. Ions having energies from 50 to 20,000 electron volts and masses from one to 32 were detected. By increasing the gain of the thermionic amplifier electrons could be counted. With still more gain single photons were counted. The multiplier tube has an extremely low background counting rate. Because a pressure of 10^{-6} mm of Hg is maintained in the counter, it can be connected directly to the vacuum system through which the electrons or positive ions are accelerated. The absence of a thin window between the counter and the vacuum system should be a great advantage in experiments dealing with low energy positive ions or electrons.

INTRODUCTION

IN RECENT years many of the problems of modern physics have required the measurement of very small currents of positive ions or electrons in a vacuum system. Various types of electrometers and electrometer tube amplifiers have been used to measure the small ion or electron currents collected by a Faraday cage within the vacuum tube. In this manner intensities as low as 10^{-17} ampere have been detected. However, if lower intensities are to be used, it becomes necessary actually to count the individual ions or electrons. The Geiger-Mueller tube, proportional counter, ionization chamber and Wilson cloud chamber have been used for this purpose. Since the operation of all these instruments depends upon the ionization produced in a suitable gas by each particle, they must be separated from the vacuum tube by a window capable of withstanding a difference of pressure of at least a few cm of Hg. Moreover, this foil must also transmit a large proportion of the particles without a great loss of their energy. These two requirements prove to be serious whenever the ions have energies less than a few hundred thousand electron volts and the electrons energies less than a few thousand electron volts.

For over thirty years it has been known that, whenever a beam of electrons having energies of a few hundred electron volts strikes a metal plate in a vacuum, secondary electrons are ejected. Recently, it has been shown that the secondary to primary ratio is about ten for certain surfaces. Zworykin[1] and others have used this fact in designing secondary electron multiplier tubes. These tubes usually have the sensitive surfaces covered with a thin layer of Cs-Cs_2O-Ag and, depending upon the number of electrodes, are capable of amplifying the initial current of photoelectrons by a factor of 10^6 or more. Zworykin has found that the signal-to-noise ratio of such a tube is 60 to 100 times that of the conventional photo-tube plus a thermionic amplifier. In a secondary electron multiplier tube this ratio is essentially determined by the shot noise of the photoelectric and thermionic current from the first electrode. If this emission could be reduced to a few electrons per minute, the noise contributed by this factor would be exceedingly small. The only other important source of noise would be that caused by microphonic vibrations of the electrodes and electrical leads. This can be greatly reduced by careful design. It has been shown that the lower limit of the current that can be amplified by this type of tube is determined by the thermionic current from the photoelectric surface. At room temperature this current is approximately 10^{-12} ampere per cm^2 for Cs

[1] V. K. Zworykin, G. A. Morton and L. Malter, Proc. I. R. E. **24**, 351 (1936).

cells and correspondingly less for surfaces with higher work functions. In attempting to measure still smaller currents it is most important to use metals that have essentially zero thermionic emission at room temperature.

Since it is well known that positive ions as well as electrons are able to eject secondary electrons from metals, a secondary electron multiplier should be capable of multiplying the original number of secondaries sufficiently to form a pulse large enough to be easily amplified by a conventional thermionic amplifier. This would enable individual ions or electrons to be counted in a vacuum.

The electrodes of a tube to be capable of detecting single particles should have the following characteristics: a large work function, a secondary electron to primary electron ratio much greater than unity, a melting point sufficiently high that the surface can be outgassed by heating in a vacuum. The first requirement is necessary to insure both an extremely small thermionic emission at room temperature and also a surface that is not sensitive to light in the visible region. In addition, the surface should be sufficiently stable as to be unharmed by a short exposure to air. In the hope of finding such a surface the secondary electron to proton ratio for a number of metals was investigated.[2] Beryllium was found to satisfy all the requirements exceedingly well. This metal has a secondary electron to proton ratio of about eight, can be heated to a red color in a good vacuum without melting and oxidizes slowly when it is exposed to the air. Mann[3] has found the photoelectric work function to be 3.92 electron volts. Consequently, a Be surface will not be sensitive to light in the visible region.

Bay[4] has given a short report of an attempt to count single photons with a secondary electron multiplier tube having electrodes coated with Cs. In order to reduce the extremely large background current it was necessary to immerse the tube in liquid air. This reduced the background to 40 electrons per minute. Single photons could be counted when a light source was placed near the tube. It is evident that the necessity of using liquid air with this type of tube would be a serious disadvantage in many experiments. He has also described an experiment with a tube having nickel electrodes covered with a layer of barium oxide. The use of this surface reduced the thermionic emission sufficiently so that at room temperature the background counting rate was about five electrons per minute. It was possible to count the individual electrons emitted from the cathode when it was illuminated with a very weak beam of light or when it was heated.

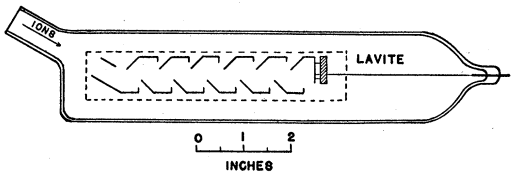

FIG. 1. The electrode arrangement of the secondary electron multiplier tube.

THE SECONDARY ELECTRON MULTIPLIER TUBE

The design chosen for the secondary electron tube is similar to that used by J. R. Pierce.[5] Since this type of tube uses two-dimensional electrostatic fields, the electron optical system can be represented by a mechanical model. A thin rubber sheet is held in a horizontal plane by a metal frame. If small sections of this sheet are given vertical displacements, it can be shown that the relative heights of these areas correspond to the difference of the potentials of similar electrodes in an electron optical system. Then the slope of the sheet will correspond to the electrical field strength. A suitable electrode design was found by constructing a model which was covered with a stretched rubber sheet. The electron paths were traced by allowing small steel balls to roll from one electrode to the succeeding one at a lower elevation. The electrode shape was altered until a ball leaving any point on the inner surface of an electrode arrived at the corresponding point on the next.

A diagram of the actual tube is shown in Fig. 1. The electrodes are of thin nickel sheet with the inner surfaces covered with Be. It was found that the best method of preparing these surfaces was to form the electrodes in a suitable press and then place them in a vacuum furnace. After they

[2] J. S. Allen, Phys. Rev. **55**, 336 (1939).
[3] M. M. Mann, Phys. Rev. **51**, 120 (1937).
[4] Z. Bay, Nature **141**, 284 (1938); **141**, 1011 (1938).
[5] J. R. Pierce, Bell Lab. Record **16**, 305 (1938).

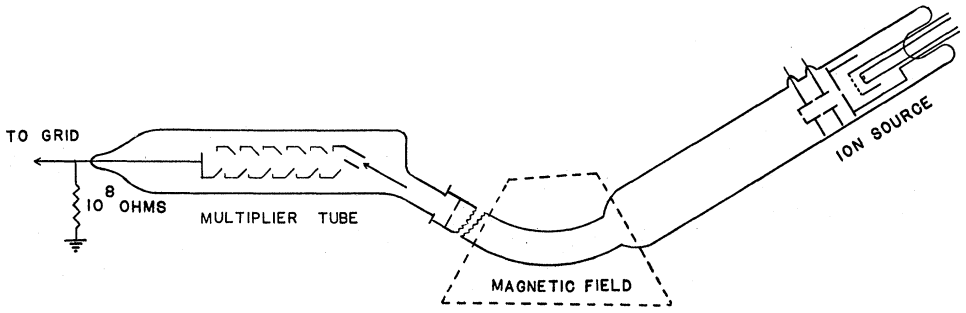

FIG. 2. The electron multiplier tube connected to the end of a magnetic spectrograph.

had been heated to a high temperature for several hours they were placed immediately in another vacuum system and a thin layer of Be was evaporated on them from a tantalum wire. The Be surfaces probably became covered with a thin layer of oxide when they were exposed to the air. Since the oxide has a very high melting point it was not removed when the electrodes were outgassed in the completed tube. The electrode system was held firmly in place between two slabs of fired lavite shown by the dotted lines. The final collecting electrode was supported on a small bar of lavite between the two flat lavite sheets. This electrode as well as the wire through the end of the tube was completely shielded from the other electrodes by guard ring insulation and by an electrostatic shield on the inner surface of the glass tube. The leads to the other eleven electrodes were brought out separately through glass tubes sealed to the main tube. The tube was evacuated continually by means of a small, three-stage, oil diffusion pump. A pressure lower than 10^{-6} mm of Hg was maintained in the tube for most of the measurements. Each electrode was kept about 300 volts positive with respect to the preceding one by taps from a potential divider of eleven 0.3-megohm resistors in series. The necessary voltage was supplied by a stabilizer of the Evans[6] type with the positive side at ground potential.

In order to measure the amplification factor of this tube it was connected to the end of a proton accelerating tube and a beam was allowed to hit the first electrode. The positive ion current to the first electrode was measured with a galvanometer and the final electron current was read on a microammeter. With 330 volts per section an output of 200 microamperes was obtained for an input of 2×10^{-9} ampere of 100-kev protons. This represents a multiplication factor of 10^5. This factor is consistent with a gain of about ten for the first and between two and three for the ten succeeding electrodes. According to the author's data[2] for the secondary electron to proton ratio and the recent value of Kollath[7] for the secondary electron to primary electron ratio for Be, the maximum gain for the first electrode should be 16 and about 4.5 for the others. Thus, the tube is about 60 to 70 percent efficient. Since the electron optical system has essentially two-dimensional electrostatic focusing, some of the electrons must be lost at the edges of the electrodes near the lavite sheets. It was found that the full amplification was not obtained until the tube had been thoroughly outgassed by heating with an induction furnace. The background current of this tube could not be detected with a galvanometer having a sensitivity of 5×10^{-10} ampere per mm deflection. Later experiments showed that the output could be connected directly to the floating grid of a W. E. 259 B tube without changing the plate current. This indicated an extremely small background current.

In order to test the spectral sensitivity of the tube a quartz window was waxed over the opening. When a quartz Hg arc was placed about three feet from the window an output 10^{-7} ampere was obtained. No output current could be measured when a 60-watt tungsten lamp was placed directly in front of the quartz window.

[6] R. D. Evans, Rev. Sci. Inst. **5**, 371 (1934).

[7] R. Kollath, Ann. d. Physik **33**, 285 (1938).

Positive Ion Counting

Figure 2 shows the arrangement used for the counting of positive ions and electrons. The secondary electron multiplier was waxed to the end of a simple mass spectrograph. The lead from the final collecting electrode was connected to the grid of the first W. E. 259 B tube of a Dunning type amplifier. A grid leak of 10^8 ohms was used. The ions were produced by the ionization of the residual gas in the ion source of the magnetic spectrograph. Usually an electron current of 10 to 20 microamperes was sufficient to produce a large number of ions. Only a small fraction of this current actually was effective in producing the ions in the immediate region of the slits. The voltage used for accelerating the ions was obtained from a power supply capable of producing 20 kv.

Since a pressure less than 10^{-6} mm of Hg was maintained in the vacuum system, it was necessary to outgas the multiplier tube very infrequently. This was done by disconnecting the first stage of the linear amplifier from the tube. An induction coil could then be slipped over it and the electrode system heated to a dull red color for several minutes. After the tube had been outgassed it was possible to operate it without further heating even after the system had been exposed to the air for several hours.

When the ions were accelerated by a few thousand volts and the magnet current adjusted so as to allow ions of mass one to enter the counting tube large pulses were seen on the oscillograph screen. These were of about the same magnitude as those observed when alpha-particles entered an ionization chamber one cm deep connected to the linear amplifier. Since the counting rate could be reduced to a few per minute by decreasing the electron current in the ion source, it seemed evident that the multiplier tube was counting single ions. In order to see if this tube was equivalent to the conventional method of measuring the ion current in a mass spectrograph, several spectral curves were obtained by measuring the counting rate as a function of the current through the magnet. The energy of the ions was about three kev. Three such curves are shown in Fig. 3. Since the final slit in the mass spectrograph was three mm wide, the peaks are rather broad. A number of peaks were observed, of which the highest were due to O_2^+ ions. In order to fix the mass scale a small quantity of He was introduced into the system. A peak at mass 4 was observed. This disappeared in about thirty minutes. There apparently was little difference in the height of the pulses due to ions of different masses. A most useful characteristic of this tube is its exceedingly low background counting rate. This was less than one count in five minutes.

It is important to determine the minimum energy that a positive ion may have and still produce sufficient secondaries to be counted. Since the first electrode of the secondary electron tube was always about three kv negative with respect to ground, it was necessary to insulate the mass spectrograph and connect it to this electrode. By suitable adjustment of the accelerating voltages the energy with which the ions hit the first electrode could be varied from a few volts up to 20 kv. The gain of the linear amplifier was calibrated by placing known voltages from a 1000-cycle oscillator on the grid of the first tube. The magnet current was adjusted so as to allow ions of mass 2 to enter the secondary electron tube and then the negative grid bias of the first pair of thyratrons in the scale-of-eight counter was increased until the counting rate decreased to zero. This bias corresponded to the height of the largest pulses produced by molecular hydrogen ions of a given energy. This should also correspond to the maximum number of electrons ejected from the first electrode by an ion. Fig. 4 shows the variation of the maximum pulse height with the energy of the ion. The maximum height of the pulses was also observed visually on the

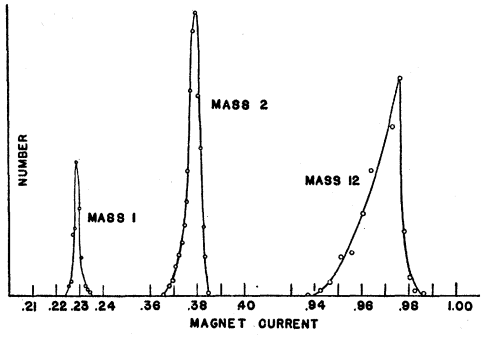

Fig. 3. The peaks due to ions of mass 1, 2 and 12.

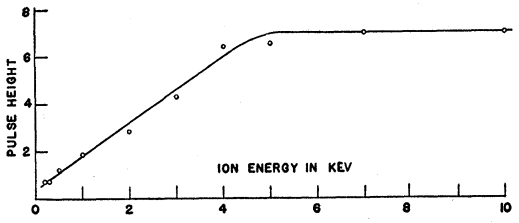

FIG. 4. The variation of the maximum pulse height with the energy of the positive ion. The height of a pulse is proportional to the number of secondary electrons ejected from the first electrode by a positive ion.

oscillograph screen for energies up to 20 kev. The results indicated that the yield of secondaries does not change much from 5 to 20 kev. The slope of the lower part of the curve is approximately equal to that of the curve obtained by Healea and Chaffee[8] for the secondary electron yield from hot Ni bombarded by molecular hydrogen ions having energies from 400 to 1600 electron volts.

It was noticed that the pulses due to ions of mass 1 and mass 2 had very nearly the same height. The mass 2 pulses should be about twice the height of those due to mass 1 ions if the molecular ion dissociates at the metal surface into two atomic ions of half the energy plus an electron. In order to find the reason for this discrepancy the secondary electron to positive ion ratio of a copper plate was measured in the usual manner. This plate was bombarded with mass 1 and mass 2 ions having energies from 25 to 75 kev. At 75 kev it was found that a molecular ion produced only 1.7 times as many secondaries as an atomic ion of the same energy. This ratio decreased with the energy to a value of 1.4 at 25 kev. The value at 75 kev is in agreement with the recent measurements of Hill, Buechner, Clark and Fisk[9] of the yield of secondaries from various metals bombarded by ions of mass 1 and mass 2. From these results it is evident that a molecular ion does not always act as two separate ions plus an electron after it has entered the surface of a metal.

The amplification of the secondary electron tube was determined as a function of the voltage between successive electrodes by measuring the heights of the largest pulses seen on the screen of the oscillograph. The ion-accelerating voltage and the current through the magnet were kept constant. Fig. 5 shows the variation of the pulse height with the secondary electron tube voltage. It is evident that the multiplication of the tube increases rapidly with the voltage per stage. This is due to the fact that the secondary electron to primary electron ratio for Be increases with the energy of the primaries and reaches a maximum at about 450 volts. When the voltage per stage was 135 the pulses were only about twice the height of the noise level due to the combined thermionic and secondary electron amplifiers. This determines the lower limit of the secondary electron tube voltage. During these measurements the gain of the thermionic amplifier was approximately linear.

ALPHA–PARTICLE AND PROTON COUNTING

The following experiment was performed in order to compare the operation of the multiplier tube with that of the ion chamber so widely used for counting alpha-particles and protons. A thin mica window was placed over the end of the multiplier tube and then it was placed near the target of a proton accelerating tube. Alpha-particles of approximately 8.6 cm range were obtained by bombarding a LiOH target with 200-kev protons. These entered the multiplier tube after passing through an absorption tube. Protons of approximately 15 cm range were obtained by bombarding a NaOD target with deuterons. Fig. 6 shows the range numbers curves determined in this manner. Curves A and B were obtained with the multiplier tube while C and D were taken from a paper by Oliphant,

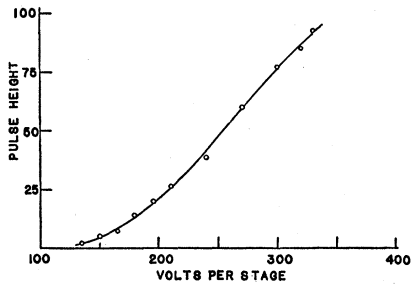

FIG. 5. The variation of pulse height with the voltage per stage of the multiplier tube.

[8] M. Healea and E. L. Chaffee, Phys. Rev. 49, 925 (1936).
[9] A. G. Hill, W. W. Buechner, J. S. Clark and J. B. Fisk, Phys. Rev. 55, 463 (1939).

Kempton and Rutherford.[10] In this case an ionization chamber was used. It is evident that the curves taken with the multiplier tube are entirely similar to those obtained with a conventional integral ion chamber.

Electron Counting

The secondary electron tube was waxed onto the end of the mass spectrograph as before and the accelerating voltages and magnet current reversed so as to allow electrons to enter the counting tube. Since the electrons were retarded after they left the mass spectrograph by the voltage of the first electrode, they were accelerated by voltages greater than three kv. When the filament in the ion gun was heated to a dull red a high counting rate was observed. The tube was able to count single electrons having energies from a few hundred to six thousand electron volts. The background counting rate was still practically zero. The maximum height of the pulses due to electrons was approximately one-seventh that of those due to positive ions of energies greater than five kev.

Photon Counting

When the gain of the linear amplifier was sufficiently high so that a positive ion would produce large pulses on the oscillograph screen and a source of gamma-rays was placed near the multiplier tube, very small pulses could be seen. These were less than one-tenth the height of the positive ion pulses. However, when the gain of the linear amplifier was increased large pulses were obtained without the background noise becoming serious. The background counting rate still had the same low value as before. Since a photon can eject only one electron from the first electrode while a positive ion or an electron can eject a number, the photon pulses will always be much smaller than those due to the ions or electrons.

Conclusion

A secondary electron multiplier tube has been developed and has proved to be a reliable instrument for counting single positive ions, electrons and photons. Since the counting rate does not depend on the voltage across the tube, reproducible results should be obtained. The necessity of separating the counter from the vacuum system by one or more thin windows has been eliminated.

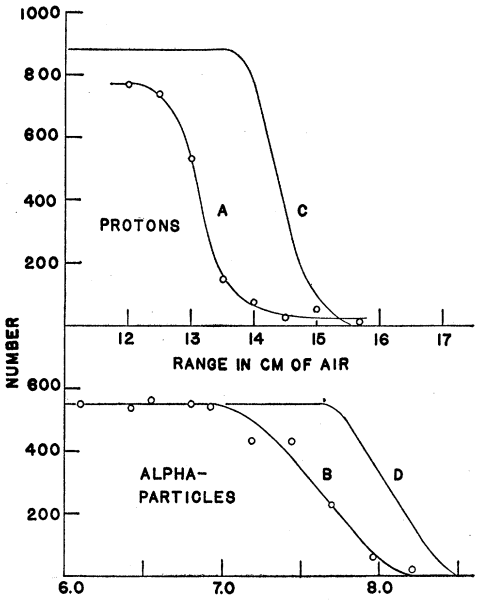

FIG. 6. Range numbers curves for alpha-particles and protons. Curves A and B were taken with the multiplier tube while C and D were taken with an ionization chamber. Curves A and B have been displaced to the left in order to compare them with C and D.

The magnitude of the pulses produced by the multiplier tube when counting ions was obtained by placing known voltages of 60 and 1000 cycles across the 10^8-ohm grid lead of the first tube of the amplifier. An input of 0.05 volt was needed to produce an output of the same magnitude as that of the ion pulses. Because of this relatively large voltage special tubes are not necessary to amplify the pulse from the multiplier tube. An amplifier of the type used to amplify the pulses from a Geiger-Mueller tube should be sufficient.

In conclusion, the author wishes to thank Professors John T. Tate and John H. Williams for many helpful suggestions and for the apparatus used in these experiments. Thanks are also due to Mr. James F. Marvin for his aid in taking some of the observations.

[10] M. L. E. Oliphant, A. R. Kempton and Lord Rutherford, Proc. Roy. Soc. **149**, 406 (1935).